CLAIMS

What is claimed is:

1. An optical apparatus, comprising:
a semiconductor device substrate;
a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and
an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding,
wherein a proximal portion of the end-coupled waveguide includes at least one of a) waveguide cladding material between the device end face and a proximal end of the waveguide core, and b) waveguide core material on the device end face extending upward from the waveguide core away from the substrate.

2. The apparatus of Claim 1, wherein the proximal portion of the end-coupled waveguide includes waveguide cladding material between the device end face and the proximal end of the waveguide core.

3. The apparatus of Claim 2, wherein the waveguide cladding material between the device end face and the proximal end of the waveguide core results in a proximal segment of the end-coupled waveguide lacking substantially complete transverse optical confinement.

4. The apparatus of Claim 2, wherein the waveguide cladding material between the device end face and the proximal end of the waveguide core forms a multimode waveguide segment.

5. The apparatus of Claim 4, wherein the waveguide core supports an optical mode substantially spatial-mode-matched with an optical mode supported by the device waveguide segment, and the length of the multimode waveguide segment is chosen so as to result in substantially spatial-mode-matched end-coupling between the

device waveguide segment and the portion of the end-coupled waveguide that includes the waveguide core.

6. The apparatus of Claim 4, wherein the waveguide core supports an optical mode larger than an optical mode supported by the device waveguide segment, and the length of the multimode waveguide segment is chosen so that it functions as a mode expander for end-coupling the device waveguide segment and the end-coupled waveguide.

7. The apparatus of Claim 2, wherein:
   the proximal portion of the end-coupled waveguide includes waveguide core material extending upward from the waveguide core away from the substrate;
   the proximal portion of the end-coupled waveguide includes waveguide cladding material between the device end face and the upwardly-extending waveguide core material; and
   the thickness of the waveguide cladding material between the device end face and the upwardly-extending waveguide core material is chosen to alter an effective reflectivity of the device end face.

8. The apparatus of Claim 1, wherein the proximal portion of the end-coupled waveguide includes waveguide core material on the device end face extending upward from the waveguide core away from the substrate.

9. The apparatus of Claim IB, wherein the waveguide core material on the device end face results in a proximal segment of the end-coupled waveguide lacking substantially complete transverse optical confinement, and the waveguide segment lacking substantially complete optical confinement is less than about 1 μm long.

10. The apparatus of Claim 1, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

11. The apparatus of Claim 1, further comprising a reflective coating formed between the device substrate and at least a portion of the end-coupled waveguide.

12. The apparatus of Claim 1, further comprising an optical coating formed between the device end face and the end-coupled waveguide.

13. The apparatus of Claim 1, further comprising a second optical waveguide optically end-coupled with the end-coupled planar optical waveguide at a distal end thereof.

14. The apparatus of Claim 1, further comprising a second optical waveguide optically transverse-coupled with the end-coupled planar optical waveguide.

15. The apparatus of Claim 1, wherein the end-coupled waveguide includes a dual-core segment.

16. The apparatus of Claim 1, wherein at least a portion of the device end face is curved in at least one dimension.

17. The apparatus of Claim 1, wherein the device end face is non-normal with respect to optical propagation along the device waveguide segment.

18. The apparatus of Claim 1, wherein:

the device end face includes an outwardly protruding portion extending along the substrate from a bottom portion of the device end face beneath a proximal portion of the end-coupled waveguide; and

at least one layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing layer thickness together yielding a desired layer surface profile for at least one layer of the end-coupled waveguide.

19. The apparatus of Claim 1, wherein the device waveguide segment functions as a transverse-mode expander.

20. The apparatus of Claim 1, further comprising:

a second device waveguide segment of the semiconductor optical device terminating at a second device end face; and

a second end-coupled planar optical waveguide formed on the device substrate at the second device end face and end-coupled at its proximal end to the device waveguide through the second device end face, the second end-coupled waveguide including a waveguide core and waveguide cladding,

wherein the proximal end of the second end-coupled waveguide includes at least one of a) waveguide cladding material between the second device end face and a proximal end of the waveguide core of the second end-coupled waveguide, and b) waveguide core material on the second device end face extending upward from the waveguide core of the second end-coupled waveguide away from the substrate.

21. An optical apparatus, comprising:

a semiconductor device substrate;

a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and

an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding; and

a reflective coating formed between the device substrate and at least a portion of the end-coupled waveguide.

22. The apparatus of Claim 21, wherein the reflective coating comprises a metallic coating.

23. The apparatus of Claim 21, wherein the reflective coating comprises a dielectric coating.

24. The apparatus of Claim 21, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

25. An optical apparatus, comprising:

a semiconductor device substrate;

a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and

an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding; and

a second optical waveguide optically end-coupled with the end-coupled planar optical waveguide at a distal end thereof.

26. The apparatus of Claim 25, wherein the second optical waveguide comprises an optical fiber mounted on the device substrate.

27. The apparatus of Claim 25, wherein the second optical waveguide comprises a planar optical waveguide formed on a waveguide substrate with the device substrate mounted on the waveguide substrate.

28. The apparatus of Claim 25, wherein the end-coupled waveguide functions as a transverse-mode expander.

29. The apparatus of Claim 25, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

30. An optical apparatus, comprising:

a semiconductor device substrate;

a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and

an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding; and

a second optical waveguide optically transverse-coupled with the end-coupled planar optical waveguide.

31. The apparatus of Claim 30, wherein the second optical waveguide comprises a planar optical waveguide formed on a waveguide substrate with the device substrate mounted on the waveguide substrate.

32. The apparatus of Claim 30, wherein transverse-coupling between the end-coupled waveguide and the second waveguide is substantially adiabatic transverse-coupling.

33. The apparatus of Claim 30, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

34. An optical apparatus, comprising:
a semiconductor device substrate;
a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and
an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding,
wherein at least a portion of the device end face is curved in at least one dimension.

35. The apparatus of Claim 34, wherein the curved portion of the end face is convex.

36. The apparatus of Claim 34, wherein the curved portion of the end face serves to increase reflective optical coupling of a device optical mode back into the device waveguide segment, relative to a substantially flat device end face.

37. The apparatus of Claim 34, wherein the curved portion of the end face serves to increase optical end-coupling between the device waveguide segment and the end-coupled waveguide, relative to a substantially flat device end face.

38. The apparatus of Claim 34, wherein the curved portion of the end face is limited in transverse extent so as to suppress higher-order device optical modes.

39. The apparatus of Claim 34, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

40. An optical apparatus, comprising:

a semiconductor device substrate;

a semiconductor optical device formed on the device substrate and including a device waveguide segment terminating at a device end face; and

an end-coupled planar optical waveguide formed on the device substrate at the device end face and end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide including a waveguide core and waveguide cladding,

wherein:

the device end face includes an outwardly protruding portion extending along the substrate from a bottom portion of the device end face beneath a proximal portion of the end-coupled waveguide; and

at least one layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing layer thickness together yielding a desired layer surface profile for at least one layer of the end-coupled waveguide.

41. The apparatus of Claim 40, wherein a lower cladding layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing lower cladding layer thickness together yielding a substantially flat upper surface of the lower cladding layer above the protruding portion of the device waveguide.

42. The apparatus of Claim 40, wherein a lower cladding layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing lower cladding layer thickness together serving to position a proximal end of a core of the end-coupled waveguide for optical end-coupling with the optical device.

43. The apparatus of Claim 40, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

44. A method, comprising:
forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;
depositing waveguide cladding material on the substrate and the device end face so that the cladding material substantially covers the device end face and forms a waveguide lower cladding layer;
depositing waveguide core material over the lower cladding layer so as to form a waveguide core, deposited waveguide core material extending upward from a proximal end of the waveguide core away from the substrate; and
depositing waveguide cladding material over the waveguide core material and lower cladding layer so as to form a waveguide upper cladding layer,
wherein the lower cladding layer, the waveguide core, and the upper cladding layer form an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end face.

45. The method of Claim 44, wherein multiple optical devices are formed concurrently on a common device substrate wafer, and multiple corresponding end-coupled waveguides are formed concurrently on the common substrate wafer, and further comprising dividing the common substrate wafer into multiple device substrates.

46. The method of Claim 44, wherein the proximal portion of the end-coupled waveguide includes waveguide cladding material between the device end face and the proximal end of the waveguide core.

47. The method of Claim 46, further comprising forming a multimode waveguide segment from the cladding material between the device end face and the proximal end of the waveguide core.

48. The method of Claim 46, wherein:

the proximal portion of the end-coupled waveguide includes waveguide cladding material between the device end face and the upwardly-extending waveguide core material; and

the thickness of the waveguide cladding material between the device end face and the upwardly-extending waveguide core material is chosen to alter an effective reflectivity of the device end face.

49. The method of Claim 44, wherein the proximal portion of the end-coupled waveguide includes waveguide core material on the device end face extending upward from the proximal end of the waveguide core away from the substrate.

50. The method of Claim 49, wherein the waveguide core material on the device end face results in a proximal segment of the end-coupled waveguide lacking complete transverse optical confinement, the waveguide segment lacking complete optical confinement being less than about 1 μm long.

51. The method of Claim 49, further comprising, before depositing the waveguide core material:

masking the lower cladding layer, leaving unmasked that portion of the waveguide cladding material covering the device end face;

forming a substantially flat upper surface of the lower cladding layer and exposing an upper portion of the device end face by removing the unmasked portion of the waveguide cladding material until it is about the same thickness as the lower cladding layer and thereby forms a portion thereof; and

de-masking the lower cladding layer,

wherein the upward-extending waveguide core material at the proximal end of the waveguide core is deposited on the exposed upper portion of the device end face.

52. The method of Claim 49, wherein waveguide cladding material deposited on the device substrate and on the device end face is at least as thick as the device waveguide segment, and further comprising, before depositing waveguide core material:

forming a substantially flat waveguide cladding material upper surface substantially flush with an upper surface of the device waveguide segment by removing waveguide cladding material by chemical-mechanical polishing; and

forming a substantially flat lower cladding layer and exposing an upper portion of the device end face by removing waveguide cladding material by cladding-material-specific etching,

wherein the upward-extending waveguide core material at the proximal end of the waveguide core is deposited on the exposed upper portion of the device end face.

53. The method of Claim 44, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

54. The method of Claim 44, further comprising forming a reflective coating between the device substrate and at least a portion of the end-coupled waveguide.

55. The method of Claim 44, further comprising forming an optical coating between the device end face and the end-coupled waveguide.

56. The method of Claim 44, further comprising optically end-coupling a second optical waveguide with the end-coupled planar optical waveguide at a distal end thereof.

57. The method of Claim 44, further comprising optically transverse-coupling a second optical waveguide with the end-coupled planar optical waveguide.

58. The method of Claim 44, wherein the end-coupled waveguide includes a dual-core segment.

59. The method of Claim 44, wherein at least a portion of the device end face is curved in at least one dimension.

60. The method of Claim 44, wherein the device end face is non-normal with respect to optical propagation along the device waveguide segment.

61. The method of Claim 44, further comprising adapting the device waveguide segment for functioning as a transverse-mode expander.

62. The method of Claim 44, wherein:
the device end face includes an outwardly protruding portion extending along the substrate from a bottom portion of the device end face beneath a proximal portion of the end-coupled waveguide; and
at least one layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing layer thickness together yielding a desired layer surface profile for at least one layer of the end-coupled waveguide.

63. The method of Claim 44, further comprising:
forming for the semiconductor optical device a second device waveguide segment terminating at a second device end face;
depositing waveguide cladding material on the substrate and the second device end face so that the cladding material substantially covers the device end face and forms a second waveguide lower cladding layer;
depositing waveguide core material over the second lower cladding layer so as to form a second waveguide core, deposited waveguide core material extending upward from a proximal end of the second waveguide core away from the substrate; and
depositing waveguide cladding material over the waveguide core material and second lower cladding layer so as to form a second waveguide upper cladding layer,
wherein the second lower cladding layer, second waveguide core, and second upper cladding layer form a second end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the second device end face.

64. A method, comprising:

forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;

depositing waveguide cladding material on the substrate so as to form a waveguide lower cladding layer;

depositing waveguide core material over the lower cladding layer so as to form a waveguide core;

depositing waveguide cladding material over the waveguide core material and the lower cladding layer so as to form a waveguide upper cladding layer, thereby forming an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide comprising the lower cladding layer, the waveguide core, and the upper cladding layer; and

forming a reflective coating between the device substrate and at least a portion of the end-coupled waveguide.

65. The method of Claim 64, wherein the reflective coating comprises a metallic coating.

66. The method of Claim 64, wherein the reflective coating comprises a dielectric coating.

67. The method of Claim 64, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

68. A method, comprising:

forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;

depositing waveguide cladding material on the substrate so as to form a waveguide lower cladding layer;

depositing waveguide core material over the lower cladding layer so as to form a waveguide core;

depositing waveguide cladding material over the waveguide core material and the lower cladding layer so as to form a waveguide upper cladding layer, thereby

forming an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide comprising the lower cladding layer, waveguide core, and the upper cladding layer; and

optically end-coupling a second optical waveguide with the end-coupled planar optical waveguide at a distal end thereof.

69. The method of Claim 68, wherein the second optical waveguide comprises an optical fiber, and further comprising mounting the optical fiber on the device substrate.

70. The method of Claim 68, wherein the second optical waveguide comprises a planar optical waveguide formed on a waveguide substrate, and further comprising mounting the device substrate on the waveguide substrate.

71. The method of Claim 68, further comprising adapting the end-coupled waveguide for functioning as a transverse-mode expander.

72. The method of Claim 68, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

73. A method, comprising:

forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;

depositing waveguide cladding material on the substrate so as to form a waveguide lower cladding layer;

depositing waveguide core material over the lower cladding layer so as to form a waveguide core;

depositing waveguide cladding material over the waveguide core material and the lower cladding layer so as to form a waveguide upper cladding layer, thereby forming an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end

face, the end-coupled waveguide comprising the lower cladding layer, waveguide core, and the upper cladding layer; and

optically transverse-coupling a second optical waveguide with the end-coupled planar optical waveguide.

74. The method of Claim 73, wherein the second optical waveguide comprises a planar optical waveguide formed on a waveguide substrate, and further comprising mounting the device substrate on the waveguide substrate.

75. The method of Claim 73, further comprising adapting at least one of the end-coupled waveguide and the second waveguide for substantially adiabatic transverse-coupling therebetween.

76. The method of Claim 73, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

77. A method, comprising:

forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;

depositing waveguide cladding material on the substrate so as to form a waveguide lower cladding layer;

depositing waveguide core material over the lower cladding layer so as to form a waveguide core; and

depositing waveguide cladding material over the waveguide core material and the lower cladding layer so as to form a waveguide upper cladding layer, thereby forming an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide comprising the lower cladding layer, waveguide core, and the upper cladding layer,

wherein at least a portion of the device end face is curved in at least one dimension.

78. The method of Claim 77, wherein the curved portion of the end face is convex.

79. The method of Claim 77, wherein the curved portion of the end face serves to increase reflective optical coupling of a device optical mode back into the device waveguide segment, relative to a substantially flat device end face.

80. The method of Claim 77, wherein the curved portion of the end face serves to increase optical end-coupling between the device waveguide segment and the end-coupled waveguide, relative to a substantially flat device end face.

81. The method of Claim 77, wherein the curved portion of the end face is limited in transverse extent so as to suppress higher-order device optical modes.

82. The method of Claim 77, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.

83. A method, comprising:
forming a semiconductor optical device on a device substrate, the optical device including a device waveguide segment terminating at a device end face;
depositing waveguide cladding material on the substrate so as to form a waveguide lower cladding layer;
depositing waveguide core material over the lower cladding layer so as to form a waveguide core; and
depositing waveguide cladding material over the waveguide core material and the lower cladding layer so as to form a waveguide upper cladding layer, thereby forming an end-coupled planar optical waveguide on the device substrate end-coupled at its proximal end to the device waveguide through the device end face, the end-coupled waveguide comprising the lower cladding layer, waveguide core, and the upper cladding layer,
wherein:
the device end face includes an outwardly protruding portion extending along the substrate from a bottom portion of the device end face beneath a proximal portion of the end-coupled waveguide; and
at least one layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the

decreasing layer thickness together yielding a desired layer surface profile for at least one layer of the end-coupled waveguide.

84. The method of Claim 83, wherein a lower cladding layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing lower cladding layer thickness together yielding a substantially flat upper surface of the lower cladding layer above the protruding portion of the device waveguide.

85. The method of Claim 83, wherein a lower cladding layer of the end-coupled waveguide decreases in thickness toward the end face, the outwardly protruding portion of the device waveguide and the decreasing lower cladding layer thickness together serving to position a proximal end of a core of the end-coupled waveguide for optical end-coupling with the optical device.

86. The method of Claim 83, wherein the end-coupled waveguide comprises a low-index planar optical waveguide.